Classical and Modern Receiver Architectures

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ABSTRACT

This article is a review of several classical and modern wireless receiver architectures used in wideband wireless communication systems. The emphasis is on configurations suitable for integration on a single silicon chip. A full understanding of the design trade-offs discussed in this article is necessary for the proper introduction of a new modulation scheme presented in the companion article, "Hierarchical QAM: A Spectrally Efficient DC-Free Modulation Scheme" [1].

INTRODUCTION

The recent surge in applications of radio frequency (RF) transceivers has been accompanied by aggressive design goals such as low cost, low power dissipation, small form factor [2], and high-speed data transfer. These goals are driven by both the need for better portability and affordability, and the ever-increasing demand for higher-speed data communications. Such objectives, together with the usual bandwidth limitations, not only call for highly integrable transceiver architectures, but also for bandwidth-efficient modulation schemes.

To address the demand for better portability and affordability, recent research has been focused toward the development of monolithic transceiver architectures, especially using low-cost complementary metal-oxide semiconductor (CMOS) technology. This approach provides the possibility of integrating analog and digital circuitry on the same chip. In addition, the use of new systems and circuit design techniques facilitates the highest levels of receiver and transmitter integration [3]. Various suitable architectures have been proposed for implementation in deep-submicron CMOS technologies [2–5].

In this article, we review several classical and recently proposed receiver architectures, and discuss their advantages and disadvantages. In a companion article [1], a new spectrally efficient dc-free modulation scheme, suitable for highly integrable receiver architectures, is introduced.

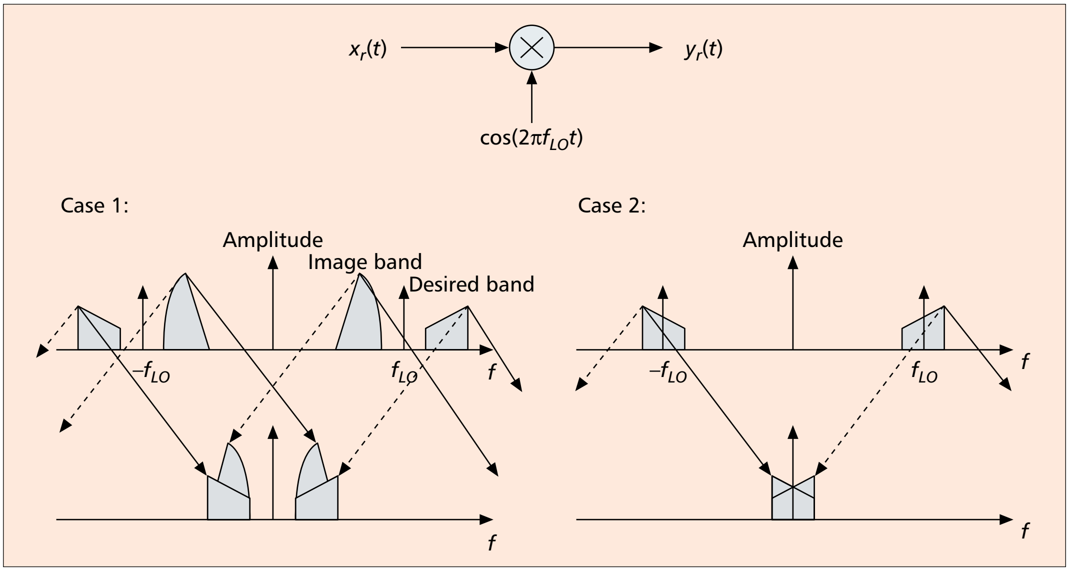

Figure 1. *Mixing a real signal with a real sinusoid for two cases, where* f_{LO} *is not equal (case 1) and equal (case 2) to the center freqeuncy of the desired signal. The spectra of the inputs of the mixer and the corresponding spectrum of the output of the mixer are shown.*

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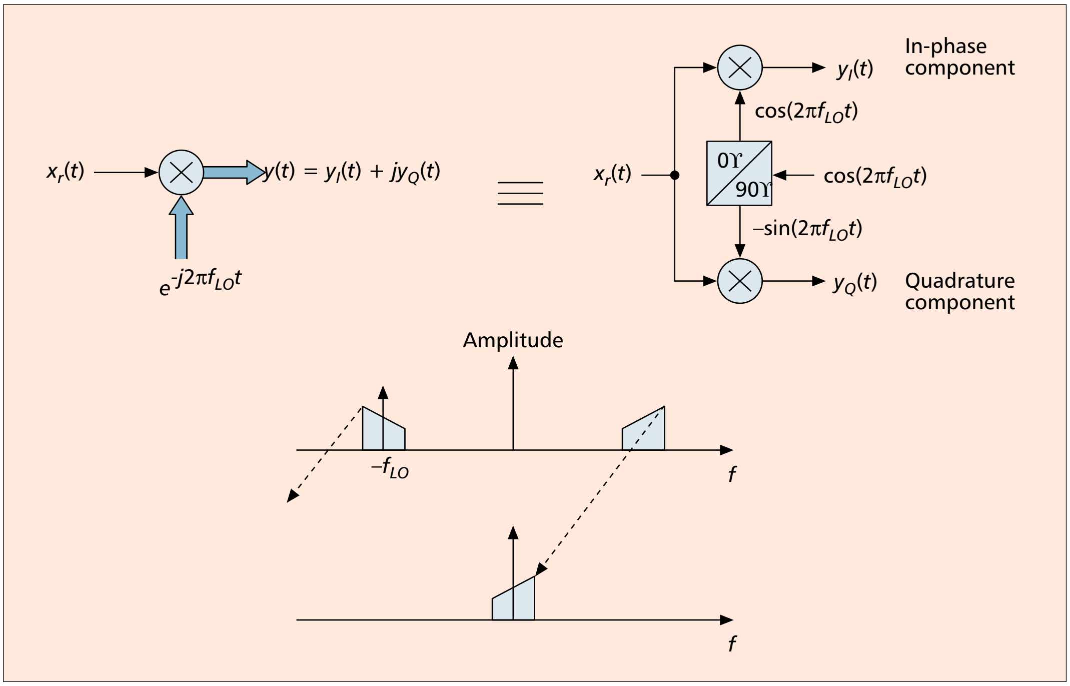


Figure 2. *Mixing a real signal with a complex exponential. The spectra of the real and complex inputs of the mixer, and the spectrum of the complex output of the mixer are shown. Here, complex signals are represented by double lines.*

To address the demand for better portability and affordability, recent research has been focused toward the development of monolithic transceiver architectures, especially using low-cost complementary metal-oxide semiconductor technology.

Background: Real and Complex Mixing

In preparation for the main discussion on receiver architectures, it is useful to review the *image band problem* related to frequency downconversion, an essential operation in any RF receiver. This will be done using complex representation of signals and complex mixing, techniques also useful for the discussions in the companion article [1].

Typically, frequency downconversion of a passband signal is performed by multiplying (mixing) the signal with a sinusoid such as $\cos(2\pi f_{LO}t)$. This is illustrated in Fig. 1 for the two cases in which the frequency of the sinusoid is different from and equal to the center frequency of the signal. Note that for a real signal, the negative and positive Fourier components are complex conjugates of each other. A multiplication in the time domain is equivalent to a convolution in the frequency domain. Since the Fourier transform of a sinusoid contains two equal-amplitude impulses symmetrically placed around zero on the frequency axis, the spectrum of the mixer output signal is the superposition of the positive and negative shifted versions of the spectrum of the input signal. As shown in Fig. 1, two frequency bands symmetric around the multiplying frequency are downconverted to the same output band. The undesired input signal band, which will be superimposed on the desired signal band after mixing, is called the *image band*. It is necessary to suppress any signal in the image band prior to the mixing operation. This is the task of the image-reject (IR) filter which usually precedes the mixer. In the special case where the multiplying frequency is equal to the center frequency of the incoming signal, the image band is the same as the signal band, and the image cannot be eliminated using filtering. Notice that the mixing operation with a real sinusoid generates additional signals above the multiplying frequency. In a typical receiver these high-frequency components (not shown explicitly in Fig. 1) are usually filtered out with a low-pass filter.

The previously discussed image problem arises due to the fact that the frequency spectrum of a real sinusoid contains impulses at both positive and negative frequencies. One way to avoid this problem is to mix the signal with a complex exponential, say $e^{-j2\pi f_{LO}t}$, which has only a single frequency component, in this case at a negative frequency ($-f_{LO}$). Although all physical signals are real, complex signals are a convenient mathematical representation for a pair of real signals [5, 6]. A complex signal, $x(t) = x_r(t) + jx_i(t)$, consists of a real part and an imaginary part, $x_r(t)$ and $x_i(t)$, respectively, where $x_r(t)$ and $x_i(t)$ are real signals and

$$j = \sqrt{-1}.$$

Complex signals are processed according to the rules of complex arithmetic. In general, they can have negative and positive frequency components totally different from each other. As an example, the complex exponential $e^{-j2\pi f_{LO}t} = \cos(2\pi f_{LO}t) - j\sin(2\pi f_{LO}t)$, has only a single negative-frequency component. Therefore, mixing a real signal with this negative-frequency complex exponential gives a complex signal whose spectrum is a shifted version of the real signal spectrum. *Theoretically*, this eliminates the image problem associated with frequency shifting when mixing with a real sinusoid.

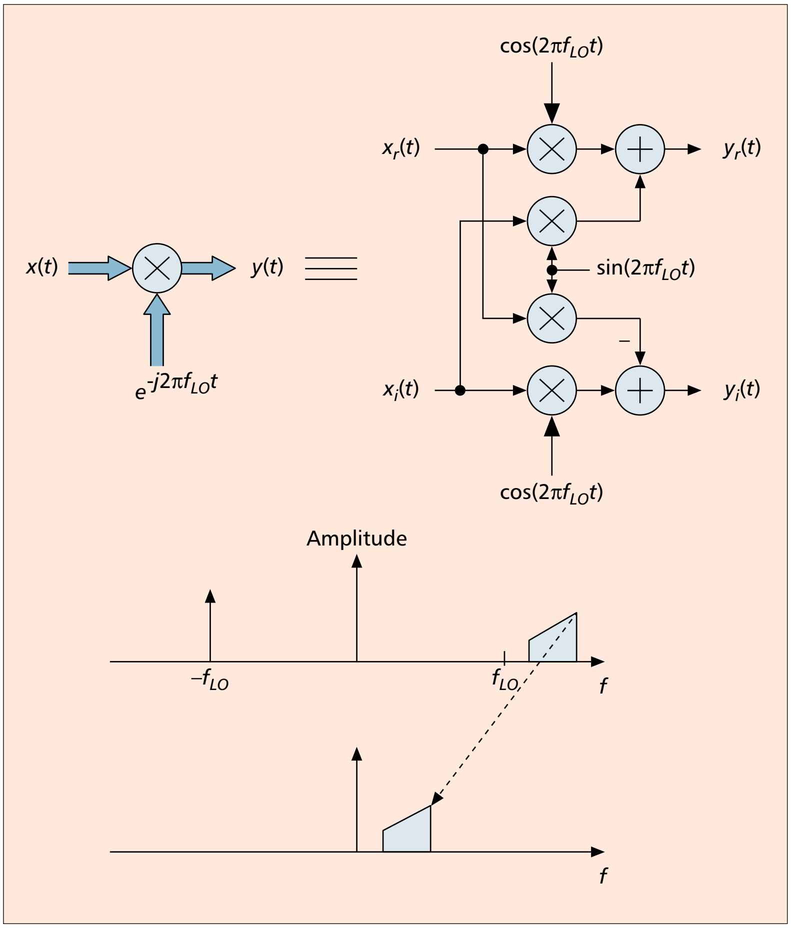


Figure 3. *Mixing a complex signal with a complex exponential. The spectra of the complex inputs of the mixer, and the spectrum of the complex output of the mixer are shown.*

The realization of a multiplier for mixing a real signal with a complex exponential requires two real multipliers, as illustrated in Fig. 2. The real and imaginary parts of the mixer output are called the *in-phase* (I) and *quadrature* (Q) components of the downconverted signal (since cosine and sine are in quadrature). In Fig. 2 the frequency of the complex exponential is chosen to be the same as the center frequency of the passband signal, for comparison with case 2 in Fig. 1. In this case there is no image problem associated with the complex mixer. As discussed in the following section, this fundamental property is used in homodyne receivers.

Now, consider the general case of mixing two complex signals $x(t) = x_r(t) + jx_i(t)$ and $z(t) = z_r(t) + jz_i(t)$: $x(t) \cdot z(t) = (x_r(t) \cdot z_r(t) - x_i(t) \cdot z_i(t)) + j(x_r(t) \cdot z_i(t) + x_i(t) \cdot z_r(t))$. A practical realization of this complex mixer using four real mixers is shown in Fig. 3. Complex mixing is used in IR mixers. These mixers are employed in some recently proposed receiver architectures, discussed later.

In some cases, only the real or imaginary part of a complex mixer output is of interest. One example is the quadrature amplitude modulation (QAM) system modulator [6]. Extracting the real (or imaginary) part of a complex mixer output can be implemented efficiently as shown in Fig. 4. Here, the complex mixer is implemented with two real mixers and one adder.

As a final point, it should be mentioned that in analyzing receivers for undesired image components, it is often necessary to isolate the positive and negative frequency components of the received signal. Figure 5 shows a block diagram of the system for converting an arbitrary complex signal into one that contains only the positive frequency components of the original signal. In this figure, the block with transfer function $-j \cdot \mathrm{sgn}(\omega)$ is the well known Hilbert transformer which shifts its input signal phase by –90° for positive frequencies and +90° for negative frequencies.

Receiver Architectures

Most of the wireless transceivers used so far are based on a conventional heterodyne architecture. These transceivers have good performance, but suffer from high production costs and require a relatively large form factor due to expensive and nonintegrable RF and intermediate frequency (IF) filters. In this section we briefly review the conventional heterodyne receiver topology along with some other recently developed receiver architectures, and discuss their advantages and disadvantages. For each particular receiver architecture, there exists a corresponding transmitter architecture with essentially the same fundamental building blocks. The exception to this regards the transmitter power amplifier, which, although important, is beyond the scope of this article. Therefore, in our review we focus on receiver structures. Further discussions of transmitter architectures can be found in [5, 7].

Conventional Heterodyne Receivers

Most of today's commercially available RF transceivers utilize some variant of conventional heterodyne architecture. In a heterodyne receiver, as shown in Fig. 6, the RF front-end (preselection) filter serves to remove out-of-band signal energy as well as partially reject image band signals. After this prefiltering, the received signal is amplified by a low-noise amplifier (LNA). The IR filter following the LNA further attenuates the undesired signals at the image band frequencies. The desired signal at the output of the IR filter is then downconverted from the carrier frequency to a fixed IF by multiplication (mixing) with the output of a local oscillator (LO). Commonly, in heterodyne receivers, high-performance, low-phase-noise voltage-controlled oscillators (VCOs) employed as LOs are realized with discrete components such as high-quality-factor (Q) inductors and varactor diodes [3].

At the output of the mixer an IF filter, typically followed by a programmable-gain IF amplifier, selects the desired channel and reduces the distortion and dynamic range requirements of the subsequent receiver blocks [3]. The signal can be shifted to baseband and demodulated as shown in Fig. 6, or alternatively further downconverted to lower IFs, and then shifted to baseband and demodulated.

Since, at the carrier frequency, the desired band and image band are separated by twice the IF, it is desirable to choose a high IF to reduce the requirements on the IR filter. In fact, if the IF is chosen high enough that the preselection RF filter can sufficiently attenuate the image band, it might be possible to directly connect the output of the LNA to the mixer without including an IR filter [7]. On the other hand, since channel selection in a heterodyne system is done at the IF, a low IF allows employment of higher-quality channel-select filters. Therefore, the choice of IF depends on the trade-off between image rejection and channel selection. Other factors influencing the choice of IF are availability and the physical size of commercial filters for different frequencies [2].

Conventionally, all the filters used in the heterodyne system are high-Q discrete component filters, such as surface acoustic wave (SAW) or ceramic filters. Compared to other more integrable receiver architectures, the heterodyne receiver has superior performance with respect to *selectivity*, a measure of a receiver's ability to separate the desired band around the carrier frequency from signals received at other frequencies, and *sensitivity*, the minimal signal at the receiver input for which there is sufficient signal-to-noise ratio (SNR) at the receiver output. This is achieved with the use of high-Q discrete components [3].

Employing high-Q elements does come with some drawbacks. A major limitation is that the off-chip IR filters have low input impedance. This requires a high drive capability for the preceding LNA, inevitably leading to more severe trade-offs between gain, noise figure, stability, and power dissipation in the amplifier [7]. Furthermore, these high-Q filters are difficult and somewhat impractical when realized at high frequencies in an integrated solution, primarily because integrated inductors have at best only moderate Q-factors. In addition, the narrowband discrete-component IF channel-select filter of the heterodyne receiver tailors the particular implementation to a specific standard [3].

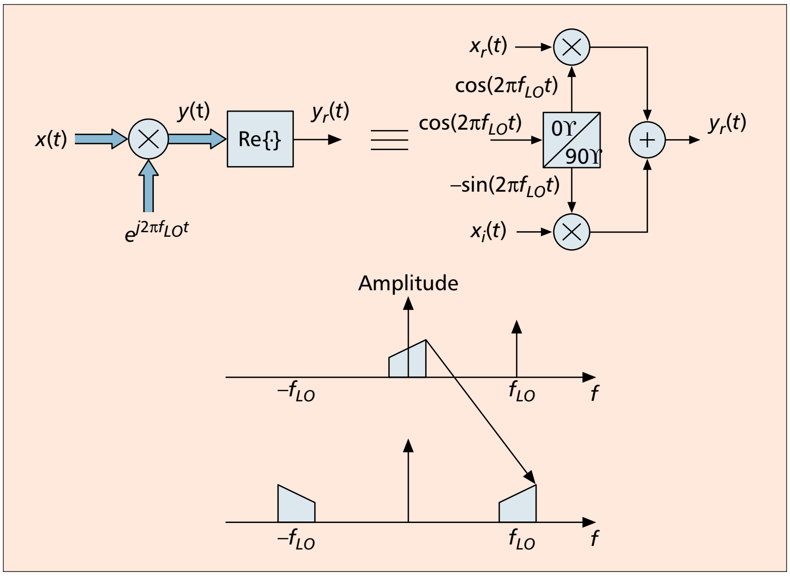


Figure 4. *An efficient implementation for a complex mixer when only a real part of the mixer output is of interest. The spectra of the complex inputs of the mixer, and the spectrum of the real part of the mixer output are shown. Note that since the final output is real signal, its spectrum is complex-conjugate symmetric.*

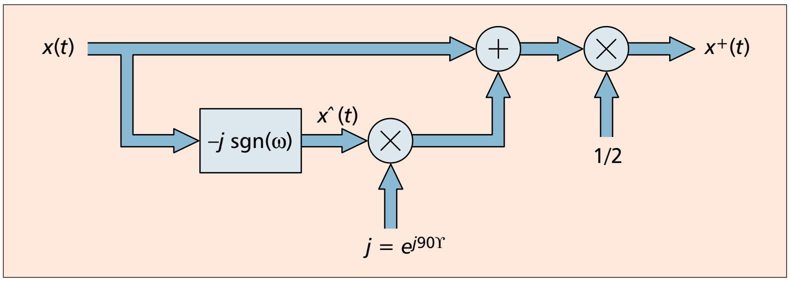


Figure 5. *A system that extracts positive frequency components of the input signal. By changing* $e^{j90°}$ *to* $e^{-j90°}$ *(i.e., j to –j) in the multiplier, the system would extract the negative frequency components of the input.*

Direct-Conversion Architecture

Direct conversion, also known as *homodyne* or *zero-IF conversion*, is a natural approach to downconverting an RF signal directly to baseband. Alternately, one can think of choosing IF to be zero. This architecture, shown in Fig. 7, employs low-pass filtering in the baseband to suppress nearby interferers and select the desired channel. The quadrature downconversion (I and Q channels) is necessary in typical amplitude and phase or frequency modulated signals because in general the two side-bands of the RF spectrum are different. Mixing with a real sinusoid would result in irreversible corruption of the transmitted information [2]. Note that quadrature downconversion is equivalent to complex mixing, discussed previously (Fig. 2).

The homodyne architecture has several fundamental advantages over the heterodyne counterpart. The intermediary IF stages are removed,

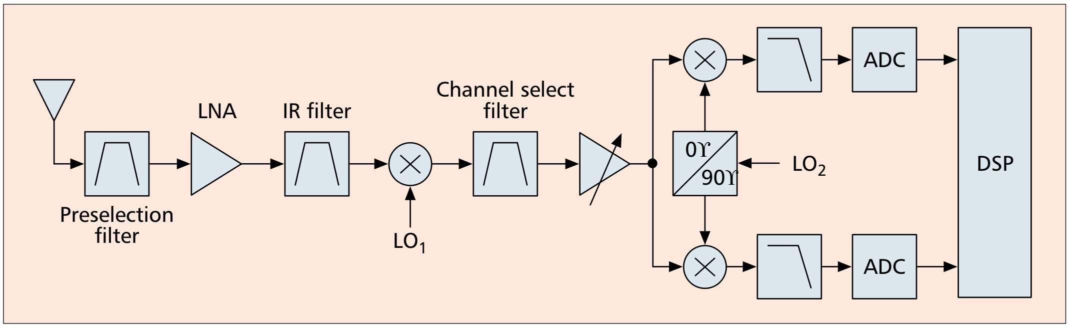
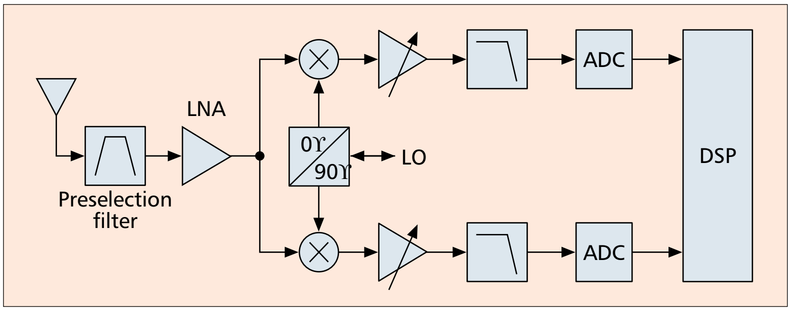


Figure 6. *A generic heterodyne receiver.*



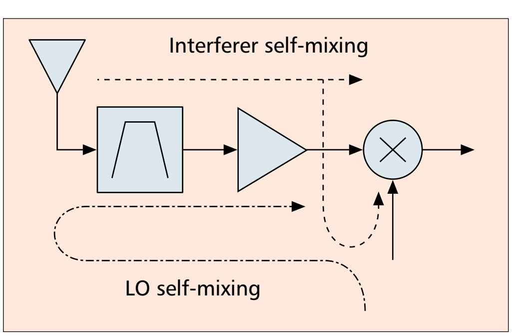
■ **Figure 7.** *A generic homodyne receiver.*

and the need for the IR filter is eliminated. Furthermore, the absence of the bulky off-chip IR filters removes the LNA requirement to drive a low impedance load. The functions of channel selection and subsequent amplification at a nonzero IF are replaced with low-pass filtering and baseband amplification, amenable to monolithic integration.

Despite this suitability for higher levels of integration, a homodyne receiver exacerbates a number of issues that either do not exist or are not as serious in a heterodyne receiver. Next, we will briefly review some of these issues.

DC-Offsets — Perhaps the most serious problem is that of dc-offset in the baseband section of the homodyne receiver [4]. These extraneous offset voltages can corrupt the desired signal and/or saturate the following stages. They arise due to the self-mixing phenomenon of the local oscillator or the in-band interferer, aside from the usual element mismatch in the signal path circuitry.

To better understand the origin of these offsets, consider the received signal path shown in Fig. 8. First, the isolation between the LO port and the inputs of the mixer and the LNA is not perfect, and a finite amount of feedthrough exists from the LO port to the other mixer input and to the input of the LNA. Known as *LO leakage*, this effect arises from capacitive and substrate coupling and, if the LO signal is provided externally, through bond-wire coupling. The leakage signal appearing at the inputs of the LNA and the mixer is now mixed with the original LO signal, thus producing a dc component at the output of the mixer. This LO self-mixing can be quite severe, and a time-varying dc-offset occurs when the LO signal leaks out through the antenna, and is radiated and reflected from nearby objects back to the receiver. A similar effect occurs if a large in-band interferer (in the passband of the RF preselection filter) leaks from the LNA output to the mixer LO port and gets multiplied by itself [7]. It should be noted that these dc-offsets exist in heterodyne receivers as well, but are mostly eliminated naturally by the IF band-pass filters.



■ **Figure 8.** *Self-mixing of the LO and/or of an interferer in homodyne receiver front-end.*

Thus, direct-conversion receivers require appropriate methods to remove undesired dc offsets. A simple approach is to use ac-coupling in the downconverted signal path. However, since the spectra of all the spectrally efficient modulation schemes currently used exhibit significant energy at dc, such signals are corrupted by ac-coupling filters [4]. A better method is the use of baseband analog and/or digital signal processing (DSP) techniques for offset estimation and cancellation [3][7]. However, these techniques add complexity and do not solve the problems associated with $1/f$ noise at low frequencies in CMOS implementations, a significant issue.

A natural system solution to the dc offset problem in direct-conversion receivers is to minimize the baseband signal energy near dc by choosing a "dc-free" modulation scheme and use ac-coupling for offset elimination. This approach has been successfully used in pager systems with frequency shift keying (FSK) modulation, despite the spectral inefficiency of FSK [4]. In the companion article [1] we introduce a new spectrally efficient dc-free modulation scheme.

LO Leakage — In addition to introducing dc offsets, leakage of the LO signal to the antenna and radiation from there creates in-band interference for other receivers using the same standard [7]. This problem becomes less severe as more sections of RF receivers are fabricated on the same chip. With differential LOs, the net coupling to the antenna can approach acceptably low levels [2].

I/Q Mismatch — As mentioned earlier, for most currently used modulation schemes, a homodyne receiver must incorporate quadrature downconversion. This requires shifting either the RF signal or the LO output by 90°. Since phase-shifting the RF signal generally entails severe noise-power-gain trade-offs [2] and is especially difficult for the wideband signals used in high-data-rate systems, it is often desirable to shift the LO output (Fig. 7). In either case, the errors in the nominally 90° phase shift and mismatches between the amplitudes of the I and Q signal paths corrupt the downconverted signal constellation, thereby increasing the bit error rate. Note that all sections of the circuit in the I and Q paths contribute to gain and phase mismatches.

To gain more insight into the effect of I /Q mismatch, and show the versatility and convenience of using complex formulation, consider the practical case where the quadrature LO generates the complex signal $x_{LO}(t) = \cos(\omega_{LO}t) - j(1+\varepsilon)\sin(\omega_{LO}t+\theta)$. Here, ε and θ represent LO gain and phase errors. One can rewrite the quadrature LO output as

$$x_{LO}(t) = \frac{1}{2}\left[1-(1+\varepsilon)e^{j\theta}\right]e^{j\omega_{LO}t} + \frac{1}{2}\left[1+(1+\varepsilon)e^{-j\theta}\right]e^{-j\omega_{LO}t}.$$

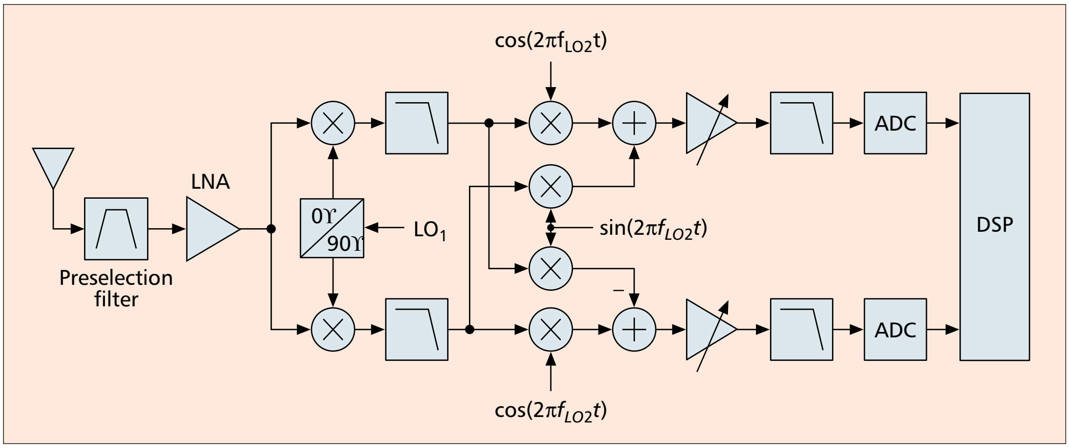


Figure 9. *A double-conversion wideband IF receiver.*

Ideally, the complex LO output should contain only the negative frequency. However, from the above expression it is apparent that, due to gain and phase errors, there is a positive frequency component with a magnitude of $|1 - (1 + \varepsilon)e^{j\theta}|/2$. This component causes interfering images and, if not compensated for, can deteriorate receiver performance. One can consider the effects of gain and phase mismatches separately. The magnitude of the undesired positive frequency component for gain mismatch is $|\varepsilon|/2$, and for phase mismatch $|\sin(\theta/2)|$, which can be approximated by $|\theta|/2$ when the phase mismatch is small.

Aside from the problems mentioned above, direct-conversion receivers are sensitive to even-order distortions. Also, since the downconverted spectrum is located around zero frequency, the flicker ($1/f$) noise of the devices has a profound effect on the SNR, a severe problem in CMOS implementations [2]. Furthermore, integrating the high-frequency low-phase-noise channel-select frequency synthesizer is difficult to achieve with low-Q VCOs available on integrated circuits [3].

Despite all these problems, direct-conversion transceivers for digital mobile phones using silicon bipolar technology have been in full production at Alcatel since 1991 [8]. The same company recently introduced a direct-conversion transceiver in a silicon germanium BiCMOS process [9] for the Global System for Mobile Communications (GSM) group of standards. In these transceivers, in order to handle the problems associated with static and dynamic dc offsets, DSP algorithms are used. These algorithms rely on the constant-envelope property of the modulation scheme used in GSM. To the best of the authors' knowledge, direct-conversion transceivers have not been used commercially in systems with nonconstant envelope modulation schemes, which are required in high-data-rate communication systems.

Wideband IF with Double-Conversion Receiver Architecture

This alternative architecture [3, 10], well suited to full integration, is shown in Fig. 9. In this receiver, after preselection filtering and amplification, all potential RF channels are complex-mixed and downconverted to IF. As discussed previously related to Fig. 2, there is no image problem. A second complex mixing is done from IF to baseband, using a tunable channel-select frequency-synthesizer. In this complex mixer, by properly adding the outputs of the real multipliers in pairs, the image frequencies are canceled while the desired channels add constructively. If the IF is chosen high enough, additional image rejection may be obtained from the RF front-end preselection filter [3].

Comparing the two integrated solutions discussed so far, in both architectures channel selection is performed at baseband, allowing the possibility of a programmable integrated channel-select filter for multistandard receiver applications. However, the wideband IF architecture has some advantages over the homodyne counterpart, which will now be discussed. Due to the fact that channel tuning is performed not using the first (RF) synthesizer but the lower-frequency (IF) LO, the RF LO can be implemented as a fixed-frequency crystal-controlled oscillator. Several techniques may be utilized to realize a low-phase-noise fixed LO with low-Q on-chip components [3]. Also, since tuning is performed with the IF LO operating at a lower frequency, the phase-noise performance of this oscillator can be significantly better than that of the tunable RF oscillator employed in a homodyne receiver. Furthermore, since in the wideband IF system there is no LO operating at the same frequency as the incoming RF carrier, the potential problems associated with LO leakage and time-varying dc offsets are minimized. Although in the wideband IF system the second LO is at the same frequency as the desired IF channel, the dc offset which results at the baseband from self-mixing is relatively constant and may be cancelled using adaptive signal processing methods [3].

The particular IR mixer used in this architecture, which is similar to the Weaver technique [11], has several advantages. First, lossy passive phase-shifting filters are not required in the signal path to generate the correct phase shift between the image and desired bands. Second, assuming again that the upconverted terms are removed, the image-rejection is very

Aside from the problems mentioned here, direct-conversion receivers are sensitive to even-order distortions. Also, since the downconverted spectrum is located around zero frequency, the flicker noise of the devices has a profound effect on the SNR, a severe problem in CMOS implementations.

As in wideband IF systems, if one employs two quadrature downconversion paths in a heterodyne receiver, then all of the required information for the separation of the wanted signal from unwanted signals, such as images, is available in the two IF signals.

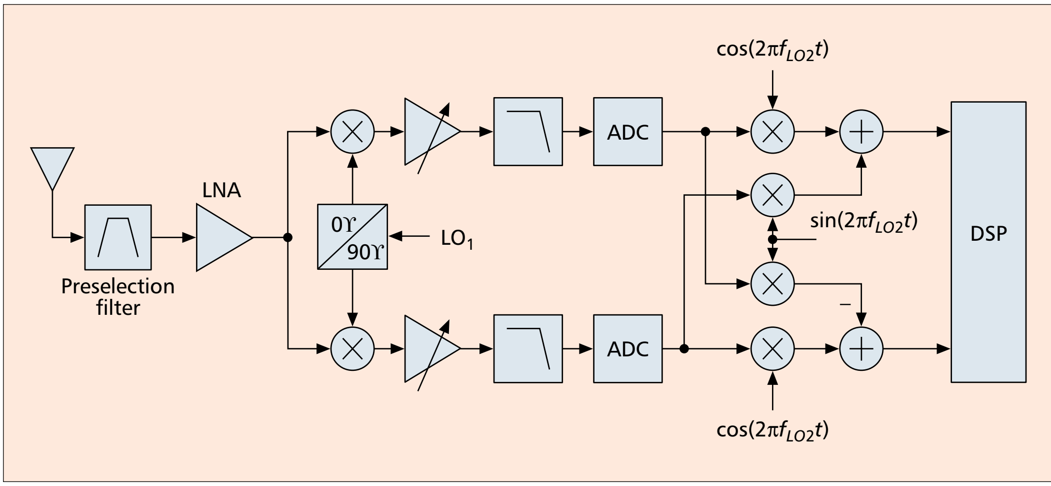


Figure 10. *A low-IF receiver.*

wideband. Also, it can be shown that the edge of the image attenuation band is set by the frequency of the first LO, which leads to the third advantage. If it is assumed that a multistandard-capable receiver is built where the frequency of the first LO can perform a course adjustment to accommodate the carrier frequency of a different standard, the image rejection will follow the first LO, and it can be thought of as a self-aligning IR mixer [3]. Note that the structure of this IR mixer (consisting of four multipliers and two adders) is the same as that of the complex mixer of Fig. 3. A detailed analysis of this IR mixer based on complex signal theory is given in [5].

The limitations of wideband IF receivers are as follows. Since the first LO is fixed in frequency, all channels must pass through the IF stage (the desired channel is selected using a second LO). This has two problematic implications: first, as a result of moving the channel selection to a lower frequency, the IF synthesizer requires a VCO with the capability of tuning across a broader frequency range as a percentage of the nominal operating frequency; second, by removing the channel-select filter at IF, strong adjacent channel interferers are now a concern for the second mixer stage as well as the baseband blocks. This implies a higher dynamic range requirement for these latter receiver stages. Also, as with conventional IR mixers, any I/Q phase and gain mismatch would degrade the performance of the receiver [3].

Low-IF Receiver Architecture

The idea behind low-IF topologies is similar to that of double-conversion wideband IF, and the goal is to combine the advantages of both heterodyne and homodyne receivers [12]. As in wideband IF systems, if one employs two quadrature downconversion paths in a heterodyne receiver, all of the required information for the separation of the wanted signal from unwanted signals, such as images, is available in the two IF signals.

Among the different low-IF topologies mentioned in [5, 10, 12], a preferred version is shown in Fig. 10. This architecture is fairly similar to that of the wideband IF architecture, although there are several subtle differences between the two. First is the choice of IF. While the IF in the wideband IF architecture is typically high, in the low-IF system the IF is chosen as low as one or two times the channel bandwidth. Note that this alleviates the dc offset problem in these two architectures compared to their homodyne counterparts, simply because after the first downconversion the wanted signal is not located around dc. Second, in the low-IF topology it is more feasible to sample the low-IF signal after the first mixer stage with a high resolution analog-to-digital convertor (ADC). Sampling at this point requires an ADC with higher resolution than that required after the IR mixer in wideband IF receivers, because in the former case the wanted signal and unwanted image are sampled. After the first mixer stage, the unwanted image can be much larger than the desired signal.

Although the low-IF architecture requires higher-performance ADCs than does the wideband IF architecture, the signal path to the ADC can be ac-coupled in the low-IF architecture, which in turn eliminates the need for complicated dc offset cancellation circuitry. *Another advantage of this low-IF topology is that part of the complex IR mixer is implemented in the digital domain with no gain and phase I/Q mismatches*. The I/Q imbalances introduced in the preceding analog sections can be corrected using adaptive techniques [13]. Therefore, this strategy shifts the hard specifications from the analog part to the ADCs. Since the performance of integrated ADCs is improving rapidly, this architecture will likely be preferred [12].

Finally, it should be noted that digitizing the received signal at the IF stage can also be employed in conventional heterodyne receiver systems. This approach is sometimes called *digital IF* [7]. In this architecture, the high ADC performance requirements are more challenging to accomplish within a reasonable power dissipation. Despite the advantage of avoiding the I and Q mismatches for typical first IFs in heterodyne receivers, this technique requires a prohibitively fast high-linearity high-dynamic-range ADC, currently limiting its utilization to only base stations [7].

CONCLUSION

In this tutorial, traditional and recent wireless receiver architectures suitable for a single-chip transceiver are reviewed. To simplify analysis of these architectures and gain more insight into their structures, complex signal representation is used. The advantages and disadvantages of each architecture are discussed with emphasis on practical considerations.

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BIOGRAPHIES

SHAHRIAR MIRABBASI [S] (shahriar@eecg.toronto.edu) received a B.Sc. degree in electrical engineering from Sharif University of Technology, Tehran, Iran, in 1990, and an M.A.Sc. degree in electrical engineering from the University of Toronto, Ontario, Canada, in 1997. During the summer of 1997 he worked at Gennum Corporation, Burlington, Ontario, Canada, on the design of cable equalizers for serial digital video andHDTV applications. He is currently working toward a Ph.D. degree in electrical engineering at the University of Toronto. His current research interests include highly integrable wireless transceiver architectures and bandwidth-efficient modulation schemes suitable for high data-rate communication systems.

KEN MARTIN [S'75-M'80-SM'89-F'91] received B.A.Sc., M.A.Sc., and Ph.D. degrees from the University of Toronto, Canada, in 1975, 1977, and 1980. From 1977 to 1978 he was a member of the scientific research staff at Bell Northern Research, Ottawa, Canada, where he did some of the early research in integrated switched-capacitor networks. Between 1980 and 1992 he was consecutively an assistant, associate, and full professor at the University of California at Los Angeles. In 1992 he accepted the endowed Stanley Ho Professorship in Microelectronics at the University of Toronto. He has co-authored a textbook entitled *Analog Integrated Circuit Design* (Wiley, 1997) in addition to three other books co-authored in cooperation with former Ph.D. students. His newest book, *Digital Integrated Circuit Design* (Oxford, 2000), was released in Oct. 1999. He has published over 100 papers and five patents. He was appointed Circuits and Systems IEEE Press Representative (1985–1986). He was selected by the Circuits and Systems Society for the Outstanding Young Engineer Award that was presented at the IEEE Centennial Keys to the Future Program in 1984. He was elected by the Circuits and Systems Society members to their administrative committee (ADCOM 1985-1987) and as a member of the Circuits and Systems BOG (1995-1997). He has served as Associate Editor of *Transactions on Circuits and Systems* from 1985 to 1987.

It should be noted that digitizing the received signal at the IF stage can also be employed in conventional heterodyne receiver systems. This approach is sometimes called "digital IF" architecture.